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13. ABSTRACT (Maximum 200 words) This project was initiated to study quantum electrodynamic effects (QED) on the interaction between quantum dots and the electromagnetic field. Investigations of quantized matter-field interactions involving self-assembled quantum dots required an advance in the understanding of the electronic structure and optical properties of strained quantum dots. Consequently much of the research carried out under this grant centered on clarifying these issues. Problems investigated included: optimization of the growth process by which the quantum dots were formed; physical characterization of the microstructure of the quantum dots so as to identify their symmetries and to enable the creation of appropriate electronic structure models; the use of these results to calculate electronic structure; and spectroscopic tests of the models.		
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Peter C. Sercel

High Resolution Optical Spectroscopy of Single Quantum Dots and Cavity-QED Effects and Lasing in Quantum Dot Microdisk Resonator Structures

ARO PECASE Program, DAA H04-96-1-0091 Period: 01 June 96– 31 Dec 2000

[1] PUBLICATIONS DURING REPORTING PERIOD:

1999-2000

Journal Articles

"The shape of self-assembled InAs islands grown by molecular beam epitaxy", Hao Lee, Weidong Yang, and Peter C. Sercel, *J. Electron. Mater.*, **28**, 481 (1999).

"Intrinsic Gap States in Semiconductor Nanocrystals" Peter C. Sercel, Al. L. Efros and M. Rosen, *Phys. Rev. Lett.* **83**, 2394, (1999).

"Inhibited carrier transfer in ensembles of isolated quantum dots", C. Lobo, R. Leon, S. Marcinkevicius, W. Yang, P.C. Sercel, X.Z. Liao, J. Zou, and D.J.H. Cockayne, *Phys Rev. B.* **60**, 16647, (1999).

"Electronic structure of self-organized InAs/GaAs quantum dots bounded by {136} facets" Weidong Yang, Hao Lee, Thomas J. Johnson, Peter C. Sercel and A. G. Norman, *Phys Rev. B.* **61**, 2784, (2000).

Invited papers submitted/presented:

"Electronic structure and optical polarization anisotropy of self-organized InAs/GaAs quantum dots" (invited) W. Yang, H. Lee, P. C. Sercel, *SPIE* paper 3325-33, Jan 27, 1999.

"Physical properties of self-assembled dots" (invited) paper Tu-A2 IEEE/LEOS Summer Topical Meeting on Nanostructures and Quantum Dots, San Diego, July 26-28 1999.

Invited Seminars

"Electronic structure of self-organized InAs/GaAs quantum dots: Breaking ground (or models) with quantum dots" (invited) P. C. Sercel, USC Department of Materials Science, April 23, 1999. \vskip0.1in

"Robust selection rules and polarization properties of excitons and exciton complexes in single quantum dots of low symmetry" (invited)

Peter C. Sercel, Workshop on the Physics of Quantum Dots for Quantum Computing, Naval Research Laboratory, Washington DC, Sept. 13-15, 1999.

Contributed papers

"Polarization anisotropy of photoluminescence from self-organized InAs/GaAs quantum dots", W. Yang, H. Lee, and P. C. Sercel, APS March meeting, Atlanta 1999.

"INTRINSIC GAP STATES IN SEMICONDUCTOR NANOCRYSTALS", P. C. Sercel, Al. Efros, and M. Rosen, APS March meeting, Atlanta 1999.

1998

Journal Articles:

"Determination of the shape of self-organized InAs/GaAs quantum dots by reflection high energy electron diffraction", Hao Lee, Roger Lowe-Webb, Weidong Yang, and Peter C. Sercel, *Appl. Phys. Lett.*, **72** 812 (1998).

"Photoluminescence study of in-situ annealed InAs quantum dots: Double-peak emission associated with bimodal size distribution" Hao Lee, Roger Lowe-Webb, Thomas J. Johnson, Weidong Yang, and Peter C. Sercel, *Appl. Phys. Lett.* **73** 3566 (1998).

Invited Seminars

"Electronic Structure and optical polarization anisotropy of self-organized InAs/GaAs quantum dots" Naval Research Laboratory Condensed matter and Radiation Sciences Division Seminar, July 9, 1998.

"The physics of self-organized InAs/GaAs quantum dots" Army Research Office Workshop on Nanostructures, Atlanta, Georgia, October 14, 1998.

Conference papers

"Electronic structure of self-organized InAs/GaAs quantum dots bounded by {136} facets", W. Yang, H. Lee, and P. C. Sercel, paper ThP-129 Proceedings of the 24th International Conference on Semiconductor Physics, Jerusalem, Israel, Aug 2-7, 1998.

"The shape of InAs/GaAs quantum dots: relation to optical properties" H. Lee, W. Yang, R. Lowe-Webb and P. C. Sercel, paper Tu1-B6, Proceedings of the 24th International Conference on Semiconductor Physics, Jerusalem, Israel, Aug 2-7, 1998.

"Strain and electronic structure of self-organized InAs/GaAs quantum dots bounded by {136} facets", W. Yang, H. Lee, R. Lowe-Webb, and P. C. Sercel, APS March meeting, Paper E32-3, Los Angeles 1998.

"Effect of growth parameters on the microstructure and optical properties of self-organized InAs/GaAs quantum dots", H. Lee, W. Yang, R. Lowe-Webb, and P. C. Sercel, APS March meeting, Paper U21-9, Los Angeles 1998.

"Morphology and electronic structure of self-organized InAs/GaAs quantum dots", H. Lee, W. Yang, R. Lowe-Webb, and P. C. Sercel
APS March meeting, Paper K38-87, Los Angeles 1998.

"Effect of in-situ annealing on the microstructure and optical properties of self-organized InAs/GaAs quantum dots grown by molecular beam epitaxy" H. Lee, W. Yang, R. Lowe-Webb, and P. C. Sercel, MRS Spring Meeting, paper S5-15, San Francisco, 1998.

"Reflection high energy diffraction study of the shape of InAs/GaAs quantum dots", Hao Lee, Peter C. Sercel, 40th Electronic Materials Conference, Z5, Charlottesville, VA., June 24-26 1998.

1997

Journal Articles

"Formation of InAs/GaAs quantum dots by molecular beam epitaxy: Reversibility of the islanding transition", Hao Lee, Roger Lowe-Webb, Weidong Yang, and Peter C. Sercel, *Appl. Phys. Lett.* **71**, 2325 (1997).

"Effect of carrier retrapping on luminescence time decays in InAs GaAs quantum dots" Weidong Yang, Hao Lee, Roger R. Lowe-Webb, and Peter C. Sercel, *Phys. Rev. B* **56**, 13314 (1997).

"Temperature and Excitation Dependence of Photoluminescence Lineshape in InAs- GaAs Quantum Dot Structures", Hao Lee, Weidong Yang, and Peter C. Sercel, *Phys. Rev. B* **55** 9757, (1997).

Conference papers

"Optical Spectroscopy of MBE-Grown InAs/GaAs Quantum Dots", Peter C. Sercel Hao Lee, Roger Lowe-Webb, Weidong Yang, APS March meeting, paper H 41 1, Kansas City, March 1997.

"Size-selective photoluminescence studies of InAs/GaAs quantum dot structures", Roger Lowe-Webb, Weidong Yang, Hao Lee, and Peter C. Sercel, APS March meeting, paper B 13 4, Kansas City, March 1997.

"Dynamics of InAs/GaAs Quantum Dot Formation by Molecular Beam Epitaxy", Hao Lee, Weidong Yang, Roger Lowe-Webb, and Peter C. Sercel, APS March meeting, paper B13 2, Kansas City, March 1997.

"Time-resolved photoluminescence study of carrier relaxation dynamics in InAs/GaAs quantum dots", Weidong Yang, Hao Lee, Roger Lowe-Webb and Peter C. Sercel, APS March meeting, paper B13 5, Kansas City, March 1997.

[2] SCIENTIFIC PERSONNEL:

Students involved in the project during 1999-2000 include
Hao Lee, Ph.D. in Physics awarded December 1998
Roger Lowe-Webb, M. S. graduated 1998.
Weidong Yang Ph. D. awarded July 1999.

[3] REPORT OF INVENTIONS:

None disclosed in the reporting period.

[4] SCIENTIFIC PROGRESS AND ACCOMPLISHMENTS:

See text beginning next page.

[5] TECHNOLOGY TRANSFER

No activities under the given description of technology transfer took place during the reporting period.

Peter C. Sercel

High Resolution Optical Spectroscopy of Single Quantum Dots and Cavity-QED Effects and Lasing in Quantum Dot Microdisk Resonator Structures

ARO PECASE Program, DAA H04-96-1-0091 Period: 01 Jan 99 – 31 Dec 1999

In this report I review major accomplishments made under research program during 1999. The last interim progress report was submitted in March 1999. Note that the PI Sercel took a leave of absence commencing October 1, 1999.

Statement of problem studied: This project was initiated to study quantum electrodynamic effects (QED) on the interaction between quantum dots and the electromagnetic field. Quantum dots used in the study were grown by strain-induced self-assembly in the InAs/GaAs material system. QED effects to be investigated were first, cavity-related modifications to the spontaneous emission rate of InAs/GaAs quantum dots in semiconductor microcavities, and second, photon number correlation's in quantum dot photoluminescence under resonant excitation.

Summary of Significant Results: At the beginning of this project in 1996, the electronic structure of InAs/GaAs dots was understood at only the most basic level, and neither the shape of these dots nor their symmetries were known. Quantitative aspects of their electronic structure such as the electron and hole level were not known as a result. In our early studies of photoluminescence dynamics of InAs/GaAs quantum dots, first reported in 1997, it became clear that the proposed investigations of quantized matter-field interactions involving self-assembled quantum dots required an advance in the understanding of the electronic structure and optical properties of strained quantum dots. Consequently much of the research carried out subsequently centered on clarifying these issues. Problems investigated included: optimization of the growth process by which the quantum dots were formed; physical characterization of the microstructure of the quantum dots so as to identify their symmetries and to enable the creation of appropriate electronic structure models; the use of these results to calculate electronic structure; and spectroscopic tests of the models.

In the course of this research we determined for the first time the shape of strain-induced InAs/GaAs quantum dots. The shape was determined using electron diffraction data and confirmed by scanning probe microscopy and transmission electron microscopy and proved to be an elongated pyramid bounded by {136} facets. This result was used to carry out the first multiband electronic structure calculations on the experimentally determined shape. In light of controversy within the field as to the shape, we showed how symmetry considerations could be used in conjunction with measurements such as polarization anisotropy that are sensitive to optical selection rules, to distinguish between models. We reported experimental measurements of polarization anisotropies that were consistent with the {136} model and inconsistent with other models widely-believed in the community. These comparisons were supported by quantitative calculations comparing each of the structural models that had literature support with our experimental data.

Interim progress reports have been transmitted covering results established through 1996, 1997, and 1998. Under the reporting instructions it is explained that previously reported technical results need not be repeated. The following list enumerates major results achieved in the last year of the grant (not previously reported).

- 1) We reported polarization spectroscopy measurements designed to test electronic structure models for self-organized InAs quantum dots. This work was begun in 1998 and continued through summer 1999. The electronic structure was calculated for several models including the {136} structure proposed the previous year by our group and compared to experimental polarization-resolved photoluminescence spectra. Good agreement with the {136} model was found: Polarization anisotropies were measured that were not explainable by other models. This study necessitated an atomistic calculation of the strain in the quantum dot structure using a valence force field model and required us to develop a finite difference implementation of the eight-band KP electronic structure method. This work is the subject of a Phys Rev. article published in 2000 and several invited talks presented in 1999.
- 2) In collaboration with Al. Efros of NRL, I made a theoretical discovery of a new class of intrinsic gap-states which occur in semiconductor heterostructures within KP based effective mass models. The work originated out of an analytical investigation undertaken to establish the behavior of KP electronic structure models as they apply to quantum confined semiconductors with strong conduction/valence band coupling, such as the InAs/GaAs system we are studying (item 1 above). These gap states, which had previously been unrecognized, can be divided into three categories: one type occurs in bare nanocrystals in narrow-gap materials characterized by strong conduction-valence band coupling; the second occurs in narrow gap heterostructures under certain special conditions; and the third occurs under special conditions at curved heterointerfaces even in the absence of conduction-valence band coupling. This work is the subject of a PRL published in September 1999.
- 3) I developed an analytical model describing the interplay of shape anisotropy, band-mixing effects, and electron-hole exchange interactions in determining the exciton finestructure in quantum dots or arbitrarily low symmetry. This work originated in an attempt to assess the importance of exchange effects in measurements of the polarization anisotropies described under point 1) above. This work was the subject of an invited talk in September 1999 at the Naval Research Lab Workshop on the Physics of Quantum Dots for Quantum Computing, organized by Henry Everitt.
- 4) Ideas developed in the course of the e-h exchange research referred to above in item 3 lead to the realization that quantum dots can provide a medium for the implementation of a "quantum phase gate". This concept, together with several good ideas for fabricating, controlling, and probing small optical microcavities developed by Mike Raymer and Hailin Wang at the University of Oregon, lead Raymer, Wang and I to submit proposals to NSF and the Army Research Office for demonstration of a quantum phase gate based on quantum dots. (These proposals were funded in 1999).